

Method for Predicting Performance of an Ion Transport Membrane Unit-Operation

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Oxygen can be recovered at high temperatures by passing hot, oxygen-containing gas, preferably air, over non-porous, mixed conducting ceramic membranes. These membranes, known in the art generically as ion transport membranes (ITM's), utilize an oxygen partial pressure differential across the membrane to cause oxygen ions to migrate through the membrane.

Membranes can be fabricated as tubes or flat plates that are arranged in modules for efficient contact with the hot compressed air. High-purity oxygen permeate and nitrogen-enriched non-permeate products are withdrawn from the modules. A comprehensive review of ion transport membranes is given by J. D. Wright and R. J. Copeland in Report No. TDA-GRI-90/0303 prepared for the Gas Research Institute, September 1990.

ITM's for oxygen separation are currently under development by Air Products and Chemicals, Inc., with the support of the U.S. Department of Energy, under contract no. DE-FC26-98FT40343. The performance of commercial-scale ITM systems can be predicted with basic operating equations and heuristics with appropriate integration into a given process, as described below.

(a) Operating Equations

Process calculations can be made from a set of operating equations presented here to describe the situation shown in Figure 1, in which an oxygen-containing inlet stream of composition, X_{feed} , at absolute pressure, P , passes through a vessel containing one or more ITM devices. Oxygen permeates the device(s) and is collected in the permeate stream at 100% purity and absolute pressure, P_{perm} . The oxygen-depleted non-permeate stream passes out of the device at composition, X_{np} , and at essentially unchanged pressure, P . The device(s) operate isothermally at temperature, T .

The oxygen-depleted non-permeate gas stream composition can be assumed or calculated from an overall recovery for the process. Recovery, R , is defined as the fraction of oxygen removed from the feed stream as a fraction of that available, or,

$$R = \frac{F_{\text{perm}}}{X_{\text{feed}} F} \quad (1)$$

where F_{perm} and F are the molar flow rates of the permeate (oxygen) and feed streams, respectively.

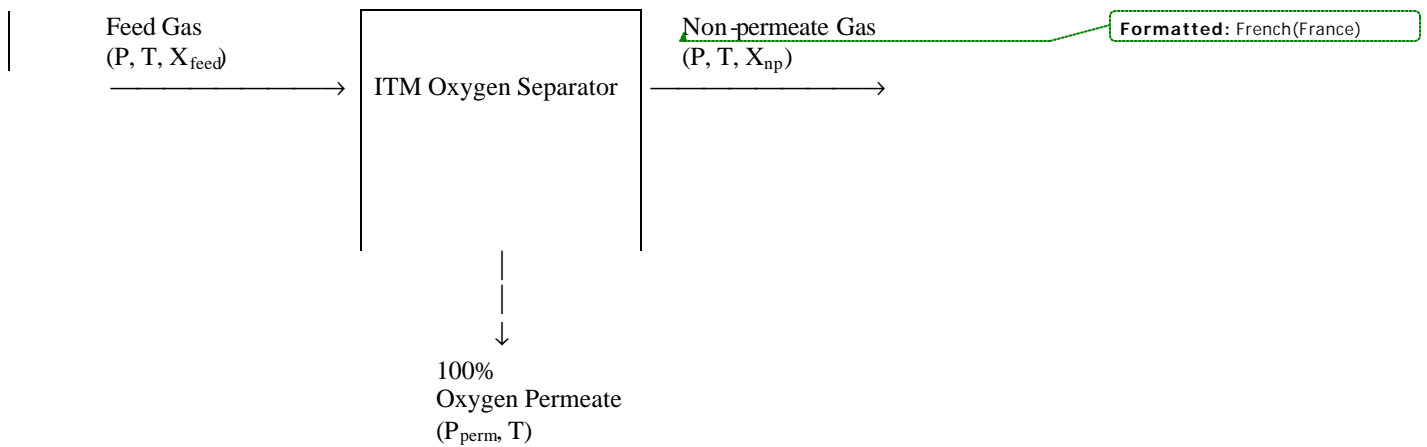


Figure 1. Process Flow Diagram of ITM Oxygen Separator

Recovery is ultimately limited by the driving force for oxygen flux. As the feed gas passes across the ITM device, the gas is depleted of oxygen. If the oxygen partial pressure in the gas falls to that in the permeate stream, the net production drops to zero. This point represents the (maximum) Theoretical Recovery point, which can be calculated as

$$R_T = 1 - \frac{(1 - X_{feed})}{X_{feed}} \frac{P_{perm}}{(P - P_{perm})} \quad (2)$$

in which R_T is the Theoretical Recovery. Consistent with many industrial separation processes, a commercial ITM separation process is best operated at 25% - 85% of theoretical recovery.

A useful heuristic for calculating separation performance by ITM is that the oxygen partial pressures in the permeate (product) and feed streams are related by

$$PX_{feed} \cong 7 P_{perm} \quad (3)$$

While significant deviation from Eq. (3) is possible, it should not be made without a detailed understanding on the ITM process or its economics. Note that P and P_{perm} are absolute pressures.

The non-permeate gas stream composition depends on R according to

$$X_{np} = \frac{X_{feed}(1-R)}{(1-RX_{feed})} \quad (4)$$

Recommended operating temperature, compositions, and pressures are summarized in Table 1 based on current development work with air and air-derived feeds. The recommended ranges depend on the specific application.

Table 1. Recommended Operating Envelope for ITM Oxygen Process Design

Parameter	Recommended Operating Range	
	Low	High
Temperature, T	800° C	900° C
Feed Pressure, P	100 psia	1000 psia
Permeate Pressure, P _{perm}	1.9 psia	100 psia
Feed oxygen fraction, X _{feed}	0.10	0.21

(b) Application of the Operating Equations

Equations (1), (3) and (4) can be used to predict the performance of an ITM process to produce oxygen, given the feed composition and desired recovery. Equation (2) is used as guide in the choice of recovery.

As an example, consider a feed stream consisting of 21% (mol.) oxygen at 300 psia flowing at 1,000,000 lbmol/h. The ITM process operates at 75% of theoretical recovery.

Based on Eqs. (2) and (3), the product pressure and theoretical recovery can be calculated as 9 psia and 88%, respectively. Accordingly, the actual recovery is 66%, or, from Eq. (1) with F = 1,000,000 lbmol/h, the process produces 139,000 lbmol/h oxygen. The calculated permeate pressure is within the recommended bounds listed in Table 1.

The oxygen concentration in the oxygen-depleted (non-permeate) stream is calculated as 8.2% (mol.), based on Eq. (4).